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300-kJ, 200-kA MARX MODULE FOR ANTARES*

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Abstract

Antares is a 100-kJ CO_2 laser driver for inertial confinement fusion experiments. The power amplification stage is pumped by an electron-beam-controlled gas discharge. There are 24 annular discharge regions, each requiring energy input of 250 kJ at 550 kV, in a 2-μsec pulse.

The energy storage module chosen for this system is a single-mesh pulse-forming network. To provide sufficient energy margin each module stores 300 kJ.

A prototype 300-kJ Marx has been built and tested at the Los Alamos Scientific Laboratory. This has been used as a test bed for components, triggering, and instrumentation.

Introduction

The Antares laser requires 24 Marx generators, each storing 300 kJ and capable of delivering more than 200 kA at 550 kV to a gas discharge load. Since reliability of this system is critical to the facility, a test and development program was implemented for critical components and a prototype Marx was built and tested. The main parameters of interest, in addition to operational reliability, were jitter and prefire rate.

Marx Design

The discharge circuit is a single-mesh pulse-forming network,[1] with 1.2-MV open-circuit voltage, 0.42-μF capacitance, and <3-μH inductance. These circuit parameters are achieved using 60 kV stages with three parallel 2.8-μF capacitors at each stage and a double-folded geometry[2] to give the required inductance. The double-folded geometry also results in good interstage capacitive coupling, which aids in achieving low jitter. In addition, the midplane trigger electrodes are coupled three stages down the Marx. The first three gaps are triggered externally. Charging is in the +/- mode, so the spark gaps run at 120 kV. The spark gaps are operated at a safety factor M = 2 (self-breakdown voltage = 240 kV) to give a low prefire rate.

Spark Gaps

The Marx switches are high-pressure gas-filled spark gaps. These switches must handle the normal discharge conditions of 200 kA and 1 coulomb, and occasional fault conditions of 400 kA and 5 C, while operating with very low jitter and low prefire rate. The individual switch jitter requirement is difficult to specify, because operation in a Marx generator involves many complicated transients. The switch prefire rate should be approximately 10^{-5} for a system prefire probability of 10^{-2} to 10^{-3}, requiring that the gaps be operated with a high safety factor.

Since low Marx inductance is important the length of the spark gap should be as small as possible to keep the capacitor stacks close together.

Spark-Gap Design

The completed spark-gap design, which evolved after many modifications, is shown in Fig. 1. This switch has been tested for 2000 shots under

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14. ABSTRACT
Antares is a 100-kJ co2 laser driver for inertial confinement fusion experiments. The power amplification stage is pumped by an electron- beam-controlled gas discharge. There are 24 annular discharge regions, each requ1r1ng energy input of 250 kJ at 550 kV, in a 2-J.lsec pulse. The energy storage module chosen for this system is a single-mesh pulse-forming network. To provide sufficient .energy margin each module stores 300 kJ. A prototype 300-kJ Marx has been built and tested at the Los Alamos Scientific Laboratory. This has been used as a test bed for components, triggering, and instrumentation.

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fault conditions with no measurable deterioration in performance. The parts are fabricated from materials as listed below:

End plates (2)	aluminum 6061-T6 plate or bar stock
Electrode standoffs (2)	aluminum bronze No. 618 bar stock
Electrode (disk) holder (1)	aluminum bronze No. 618 plate stock
Snap ring, tapered (1)	carbon steel
Electrode hold-down bolt (2)	threaded steel rod
Insulating housing (2)	cast nylon tubular bar
Compression thru-rods (6)	3/4-10 Permali "Superstud"
Compression thru-rod nuts (12)	3/4-10 Permali ME glass
Hemispherical electrodes (2)	Plansee K25 copper-filled tungsten
Trigger disk electrode (1)	Plansee K25 copper-filled tungsten

The overall length of the assembled switch is 25 cm, including the glass composition nuts used on the polyurethane/glass through-rods; the diameter of the switch is 25 cm. The main electrodes are hemispheres 5 cm in diameter with a gap spacing of 2.79 cm. The trigger disk electrode is 0.64-cm thick, 10.2-cm diam, with a 2.5-cm-diam center hole. The edge of the trigger disk center hole is machined with a full radius.

To keep weight and cost down, the end plates were made of aluminum. The trigger disk holder and main electrode standoffs were made from aluminum bronze, which is easily machineable and chemically more stable than aluminum or brass. The insulating housing was made from blue nylon because it had the best combination of mechanical properties, cost, and availability.

Because of the high current and charge transfer requirements, a high quality electrode material is required. It is known that the erosion of brass would be excessive at this duty. Several other electrode materials were considered. Their properties are shown in Table I.

When used in the short-circuit test (described below), molybdenum electrodes fractured in a few shots. We attribute the problem to moderate electrical (and thermal) conductivity combined with poor room temperature impact strength.

Zirconium copper survived, but eroded significantly in several hundred shots. Tungsten-filled copper eroded unacceptably after approx. 750 shots. Copper-filled tungsten more than exceeded the design criteria, lasting for 2000 shots with negligible erosion.

The final prototype survived 2000 consecutive operations under conditions which simulate a Marx fault. A schematic diagram of the test fixture and associated test parameters is shown in Fig. 2 A 120-kV, 27-kJ capacitor bank was switched into a low impedance circuit resulting in an oscillatory ring-down through the spark gap. This test generated a peak current of 480 kA, 9 coulombs per shot at 120 kV, a ringing frequency of 180 kHz, with a repetition rate of one shot per minute. The gap was operated with a safety factor of M = 2, requiring a pressure of 50 psig of dry air. It was purged with dry breathing air immediately after each shot. Purge duration was 10 seconds at 3.3 cfm.

After 2000 shots, the spark gap was removed from the test fixture and examined. The 5-cm diameter K25 electrode hemispheres showed insignificant wear. Black and brown surface discoloration and roughness were present indicating formations of oxides.[3,4] Cleaning the oxides from the surfaces revealed small amounts of surface pitting but no grain boundary erosion or cracks. The K25 trigger disk, 0.64-cm thick by 10.2-cm diam with a 2.5-cm-diam center hole exhibited some erosion. The hole had not enlarged. Preferential erosion was evident on a section of the surface oriented toward the negatively charged half of the capacitor bank. This erosion was in the form of localized pitting approximately 0.1-mm to 0.3-mm deep over an area of approxi-

TABLE I
METALS INVESTIGATED

Metal	Property: Electrical Conductivity	High Temp. Strength	Room Temperature Impact Strength
Molybdenum	Fair	Excellent	Very Poor
Zirconium Copper	Excellent	Poor	Good
Tungsten-filled copper matrix	Good	Poor	Poor
Copper-filled tungsten matrix	Good	Excellent	Poor

mately 1 cm^2 near the hole edge. The same oxide discoloration and roughness were present as on the hemispheres.

The interior surfaces of the nylon insulator were discolored, glazed and rough, but no cracks, burns, or electrical tracking were in evidence. It appeared as though heat had glazed the nylon, short wavelength radiation had discolored it, and hot, nonconducting metal oxides had splattered and coated the surfaces. Blue-colored powder (probably zinc oxide) had settled by gravity on the lower halves of each insulator. At the conclusion of the 2000-shot test, the dielectric strength of the nylon surface was still sufficient to hold off 120 kV for three minutes at a gas pressure of 30 psig (M = 1.2). This test was repeated three times with several full-power shots between the three-minute holding periods.

The switch was tested for jitter at different operating voltages and pressures with a 0.25-ohm $CuSO_4$ resistor installed to simulate actual operating conditions. A 500-ohm, $CuSO_4$ resistor was inserted in series with the trigger electrode to simulate circuit values in the Marx generator. The test arrangement is shown in Figs. 3 and 4, and the test results are shown in Figs. 5-11. The trigger voltage amplitude and waveform (Fig. 5) was held constant for all jitter measurements. The time spread is on the order of 10 ns. The effect of trigger amplitude on jitter is shown in Figs. 11 and 12. A Hewlett-Packard 5370-A Time Interval Counter corroborated the oscilloscope data.

Resistors

Most Marx generators have used liquid resistors for stage charging isolation and trigger coupling. We felt that liquid resistors would not provide the reliability required in this large system. Some type of solid resistor was preferred. We tested two types, wire-wound and Carborundum type AS. The test consisted of discharging a 170-μF capacitor at voltages up to 11 kV (10 kJ) into the resistor. The resistors were first soaked in transformer oil. The wire-wound resistors were Dale 225 W, 100 ohm. They failed at 1/2 kJ, by melting of the coating. The Carborundum resistors were type 889 AS (12 in. long, 1 in. diam). They failed at 3 kJ by chipping of the material. These are rated by the manufacturer at 35 kJ when operated in air. We then tested some resistors which were coated with epoxy by the manufacturer to keep oil out of the resistor body. These were run up to 10 kJ, the limit of our test facility, without failure. This provided an adequate safety margin for use in the Marx generator.

Marx Testing

A prototype Marx was built and tested to determine operating reliability, jitter, and prefire rate. Because the resistor development program was still in progress when the Marx was built, liquid resistors were used initially.

Jitter was measured using an HP-5370A time counter. The start signal was taken from the first stage of trigger amplification, a PATCO PT-70. The remainder of the trigger system consists of a PATCO TG-55 (Krytron switched spiral line) and a three-stage trigger Marx with 120-kV output, driving three 50-ohm cables, 30 ft long. The stop signal for the counter comes from a shielded single-turn $\mathring{B}$ probe placed in the Marx tank. Because of severe noise problems, this was coupled through an analog fiber-optic system.

The system rms jitter with liquid charging and trigger resistors was 12 ns. With solid charging resistors and liquid coupling resistors, the jitter was 14 ns, and with all solid resistors, jitter was 15.5 ns. All jitter measurements are after 500 to 800 shots at full energy. A set of shots was 20 to 30. The liquid resistors were mounted directly to the capacitor bus-bars. When the change was made to solid charging resistors, all the resistors were mounted on a board outside the Marx with wires going to the bus-bars. The increased inductance of this path may account for the increased jitter of the Marx.

The prefire rate has been on the order of 0.01. This seems excessive, considering that the spark gaps are run with a safety factor M = 2, and that the electrodes feel very smooth after running at full energy. Self-breakdown voltage vs pressure curves were run on new and used (500-shot) gaps. These showed only a few percent difference. Experiments are continuing using increased air flow through the gaps and 50-μm mesh filters on the air line to each gap.

References

1. Kenneth B. Riepe and Hansjorg Jansen, "Pulsed Power Systems for the LASL High Energy Gas Laser Facility," IEEE International Pulsed Power Conference, Lubbock, TX, Nov. 1976, IEEE Publication No. 76CH1147-8 REG 5.
2. Kenneth B. Riepe and Mary J. Kircher, "Design of the Energy Storage System for the High Energy Gas Laser Facility at LASL," Seventh Symposium on Engineering Problems of Fusion Research, Knoxville, TN, Oct. 1977, IEEE Publication No. 77CH1267-4-NPS.
3. G. N. Glasoe and J. V. Lebacqz, Pulse Generators, (Dover Publications, Inc., New York, NY, 1965), p. 280.
4. J. E. Gruber and R. Suess, "Investigation of the Erosion Phenomenon in High Current, High Pressure Gas Discharges," Institute for Plasmaphysik, Garching bei Munchen, IPP 4/72 (December 1969).

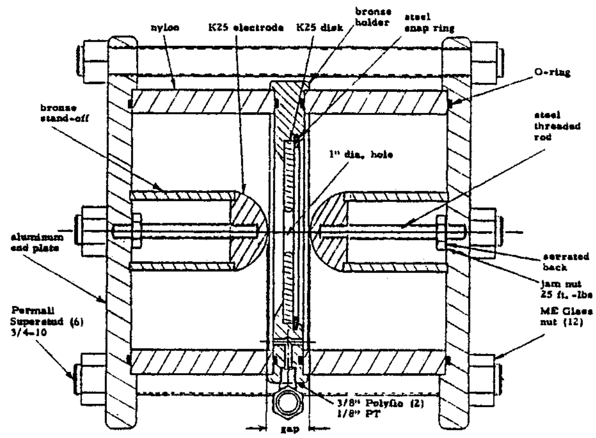
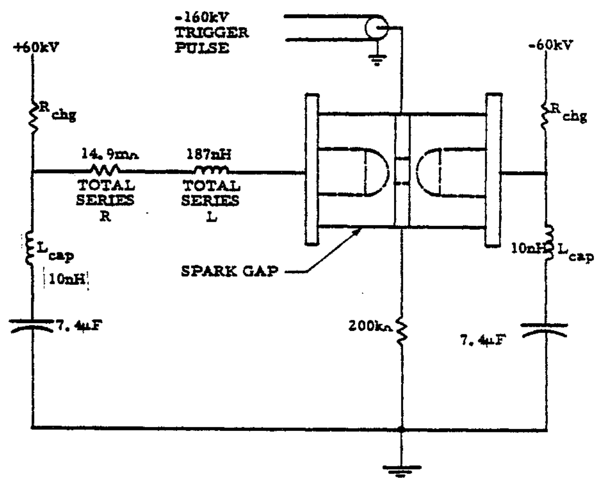
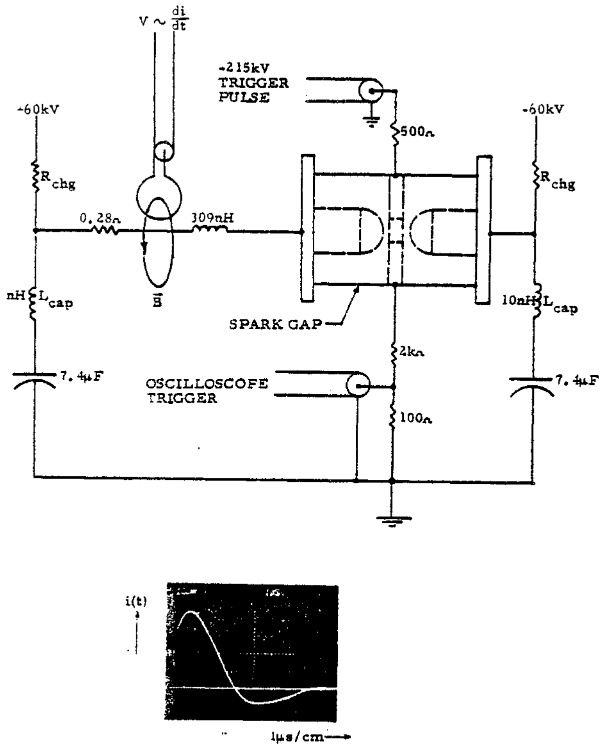


Fig. 1. The tested spark-gap design.



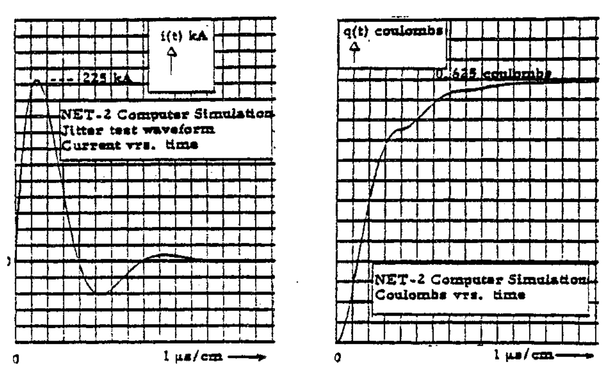
I (peak)	= 482kA
V hold-off	= 120kV
q per shot	= 9 Coulombs
Energy switched	= 27kJ
f ring-down	= 182kHz
Repetition rate	= 1 shot per minute

Fig. 2. Worst-case fault-test parameters.



CURRENT WAVEFORM

Fig. 3. Test circuit for jitter measurements.



I (peak)	=	225 kA
V holdoff	=	120 kV
q per shot	=	0.625 coulombs
Energy switched	=	27 kJ
f ring-down	=	127 kHz
Repetition rate	=	1 shot per minute

Fig. 4. Jitter test circuit parameters.

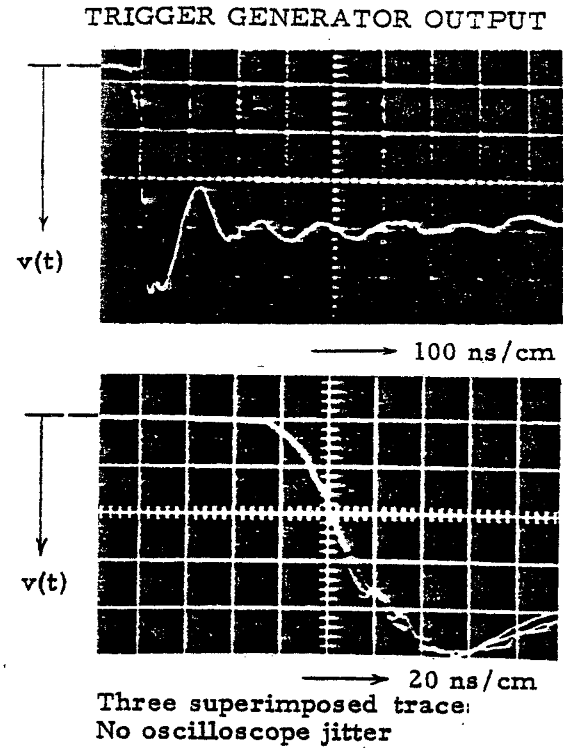


Fig. 5. Trigger generator waveform for jitter measurements.

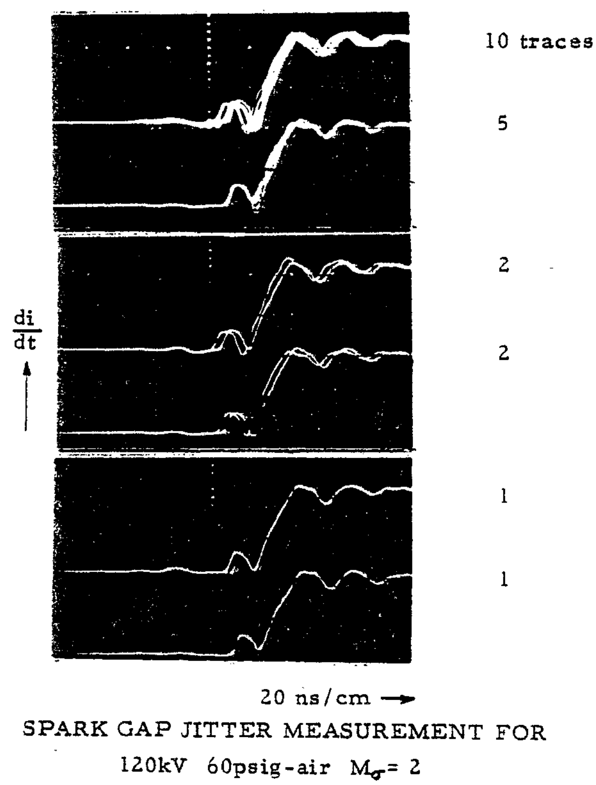
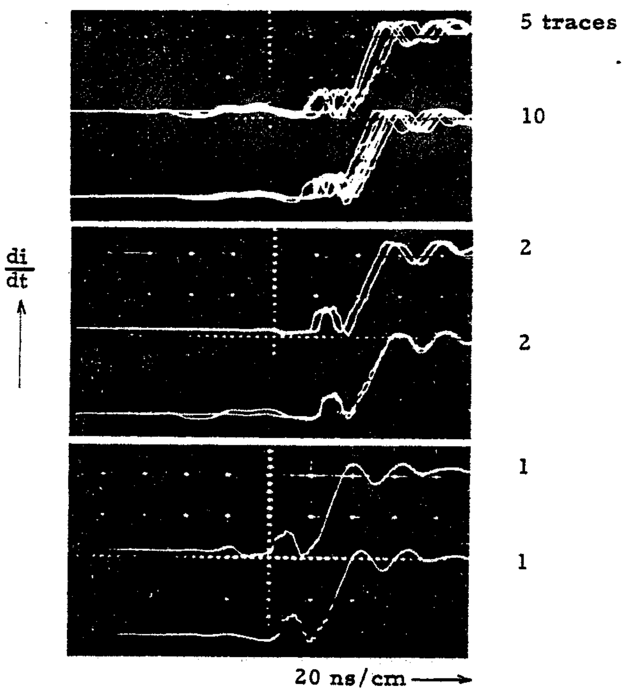
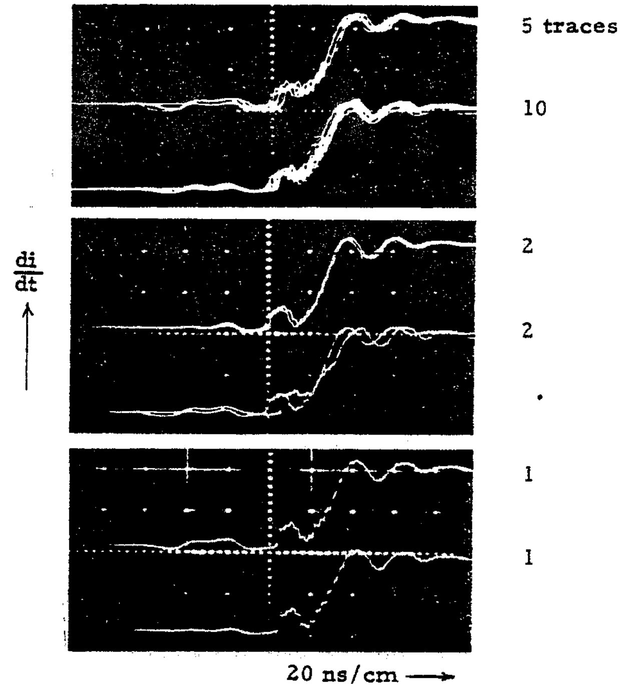


Fig. 6. Waveforms from spark-gap jitter test.



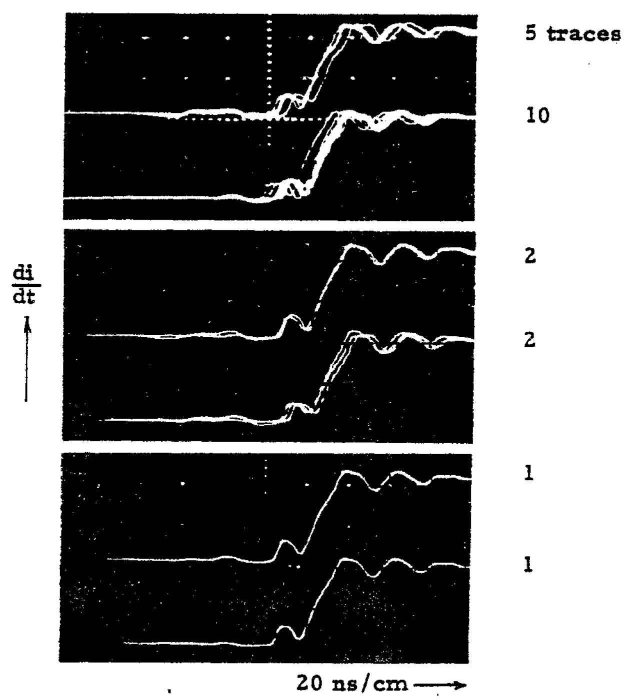
SPARK-GAP JITTER MEASUREMENT FOR
80 kV 34 psig-air $M_\sigma = 2$

Fig. 7. Waveforms from spark-gap jitter test.



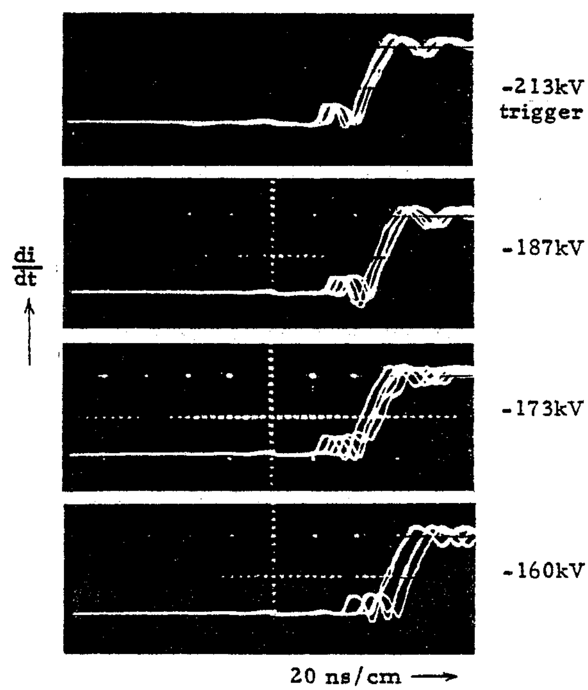
SPARK-GAP JITTER MEASUREMENT FOR
120 kV 50 psig-air $M_\sigma = 2$

Fig. 8. Waveforms from spark-gap jitter test.



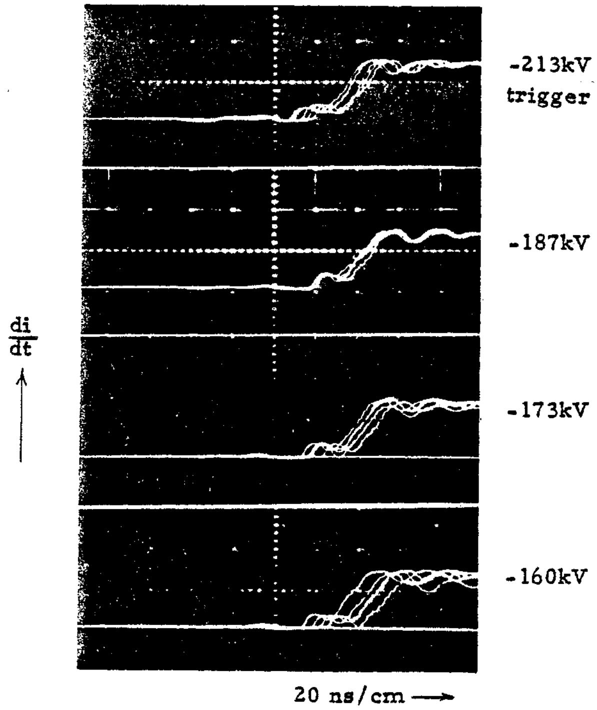
SPARK-GAP JITTER MEASUREMENT FOR
80 kV 27.6 psig-air $M_\sigma = 1.75$

Fig. 9. Waveforms from spark-gap jitter test.



JITTER vs TRIGGER VOLTAGE AMPLITUDE
120 kV 60 psig-air $M_\sigma = 2$

Fig. 10. Waveforms of jitter vs trigger amplitude.



JITTER VRS. TRIGGER VOLTAGE AMPLITUDE

80kV 34psig-air $M_\sigma = 2$

Fig. 11. Waveforms of jitter vs trigger amplitude.